BEACONS IN THE DARK: USING NOVAE AND SUPERNOVAE TO DETECT DWARF GALAXIES IN THE LOCAL UNIVERSE

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Accepted to ApJ

ABSTRACT

We propose that luminous transients, including novae and supernovae, can be used to detect the faintest galaxies in the universe. Beyond a few Mpc, dwarf galaxies with stellar masses $\lesssim 10^6 M_\odot$ will likely be too faint and/or too low in surface brightness to be directly detected in upcoming large area ground-based photometric surveys. However, single epoch LSST photometry will be able to detect novae to distances of ~ 30 Mpc and SNe to Gpc-scale distances. Depending on the form of the stellar mass-halo mass relation and the underlying star formation histories of low mass dwarfs, the expected nova rates will be a few to ~ 100 yr^{-1} and the expected SN rates (including both type Ia and core-collapse) will be $\sim 10^2 - 10^4$ within the observable (4π sr) volume. The transient rate associated with intrahalo stars will be comparably large, but these transients will be located close to bright galaxies, in contrast to the dwarfs, which should trace the underlying large scale structure of the cosmic web. Aggressive follow-up of hostless transients has the potential to uncover the predicted enormous population of low mass field dwarf galaxies.

Subject headings: galaxies: stellar content — galaxies: dwarf — supernovae: general — novae, cataclysmic variables

1. INTRODUCTION

Dwarf galaxies are believed to play several important roles in modern theories of galaxy formation. The ionizing radiation they emit at high redshift is likely essential for reionizing the universe (e.g., Madau et al. 1999; Robertson et al. 2013). At later times they contribute to the buildup of streams and stellar halos around galaxies (e.g., Johnston 1998; Helmi & White 1999). Their luminosity functions and kinematic properties place very demanding constraints on models of star formation and stellar feedback and even perhaps the nature of dark matter (e.g., Boylan-Kolchin et al. 2011; Brooks et al. 2013; Governato et al. 2015).

The relation between stellar mass and dark matter halo mass is a simple but powerful tool to help understand the distribution of galaxies in the cosmic web, the luminosity function of dwarf galaxies, the integrated efficiency of star formation, and the hierarchical growth of galaxies over cosmic time (e.g., Purcell et al. 2007; Conroy & Wechsler 2009; Behroozi et al. 2013; Garrison-Kimmel et al. 2014). Empirically-constrained stellar mass-halo mass relations imply that there exist enormous numbers of dwarf galaxies with stellar masses $< 10^6 M_\odot$ in the field (> 1 Mpc^{-3}; e.g., Behroozi et al. 2013; Garrison-Kimmel et al. 2014). Only a handful of these very low mass field dwarfs have been detected to date (e.g., Karachentsev et al. 2013).

Their low luminosities and surface brightnesses makes dwarf galaxies difficult to detect. Dwarf galaxies within a few Mpc can be resolved into individual stars. This has been the classic detection method for nearby dwarfs in the modern era (e.g., Willman et al. 2005; Martin et al. 2006; Belokurov et al. 2007; Chiboucas et al. 2009). The faintest dwarfs have surface brightness within a half light radius of $\gtrsim 27$ mag arcsec^{-2} (McConnachie 2012), making it very difficult to detect them at distances where they cannot be resolved into stars. More-

over, there are theoretical reasons to suspect that a large population of ultra-diffuse galaxies may exist beyond the detection limits of current resolved-star surveys (Bovill & Ricotti 2009; Bullock et al. 2010, Wheeler et al., in preparation). Specialized imagers can reach these faint surface brightness limits (e.g., Mihos et al. 2005; Abraham & van Dokkum 2014), and Merritt et al. (2014) recently reported the discovery of faint dwarf galaxies surrounding M101 detected in this way. However, detecting faint dwarfs in the field requires imaging large areas of the sky, and no such surveys targeting these extremely low surface brightness limits are currently planned, though clearly they would be of high value. At still greater distances dwarfs will appear as faint point sources, and so either photometric redshifts or follow-up spectroscopy is required to confirm their dwarf status.

Ongoing and planned high cadence photometric surveys such as the Palomar Transient Factory (PTF; Rau et al. 2009; Law et al. 2009), Pan-STARRS (Kaiser et al. 2002) the Zwicky Transient Factory (ZTF Bellm 2014), and the Large Synoptic Survey Telescope (LSST; Abell et al. 2009) are or will be observing large areas of the sky with the depth necessary to detect a wide class of transient objects in single epoch imaging and individual bright stars in nearby dwarf galaxies in coadded images. In this Letter we propose that the transients that will be discovered in wide field photometric surveys can be used to detect faint dwarf galaxies that would otherwise be too distant to detect with standard techniques. This proposal is similar in spirit to the idea of using transients to detect the diffuse population of stars in the halos of galaxies, groups, and clusters, often known as intrahalo stars (e.g., Gal-Yam et al. 2003; Shara 2006; Sand et al. 2012). Shara (2006) for example predicted that LSST will observe hundreds of novae associated with intrahalo stars.

2. DWARF GALAXIES IN THE LOCAL GROUP

McConnachie (2012) provided a compilation of key photometric and structural paramaters of all known dwarf galaxies (as of 2012) within 3 Mpc of the Sun. From the reported ef-

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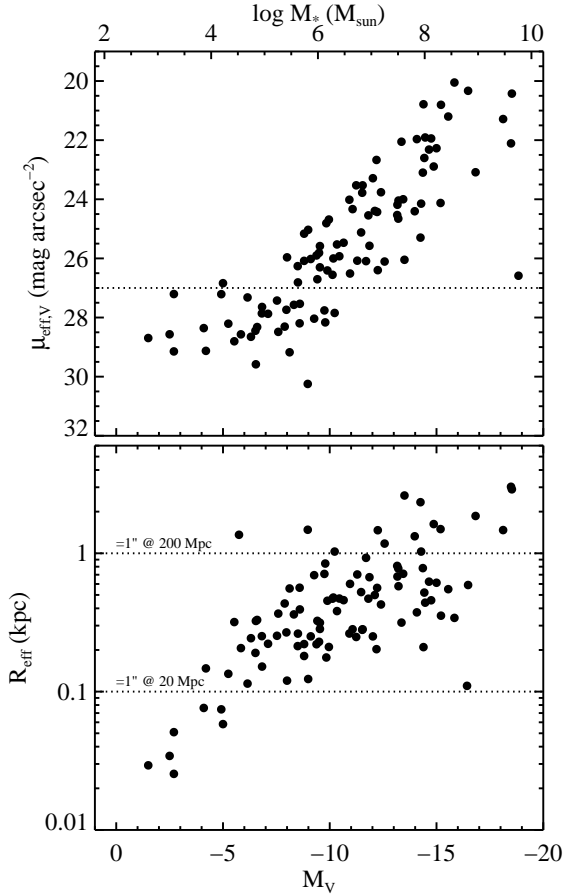[1] Department of Physics & Astronomy, University of California, Irvine, CA, USA

Figure 1. Properties of known dwarfs in the Local Group, from data compiled by McConnachie (2012). The dotted line in the upper panel marks the rough expected surface brightness limit of LSST. Stellar masses have been estimated assuming $M/L_V = 2.0$.

fective radii, magnitudes, and ellipticities we have computed the mean $V-$band surface brightness within the effective radius, $\mu_{\rm eff,V}$. The distribution of known Local Group dwarf galaxies in size-luminosity-surface brightness space is shown in Figure 1. We also translate the sizes into distances at which the size would subtend $1''$. A threshold surface brightness of $\mu_{\rm eff,V} = 27$ mag arcsec^{-2} is indicated as a rough estimate of the LSST surface brightness limit (Abell et al. 2009). Notice that the faintest known galaxies all lie at $\mu_{\rm eff,V} > 27$ mag arcsec^{-2}, suggesting that it will be difficult for LSST to detect such galaxies except where the individual stars from such galaxies can be easily detected (e.g., within a few Mpc of the Sun). In the figure we also translate the x-axis into an approximate stellar mass by assuming a $V-$band mass-to-light ratio of $M/L_V = 2.0$, appropriate for old (10 Gyr) metal-poor ([Z/H]< -1) populations (Conroy et al. 2009)[3]. Of course, for the star-forming galaxies this is a poor assumption and will result in an overestimation of the mass. These masses are only computed to guide the eye and are not used in any of the calculations below.

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[3] A Kroupa (2001) stellar initial mass function has been assumed throughout this work when quoting stellar masses and rates per unit stellar mass.
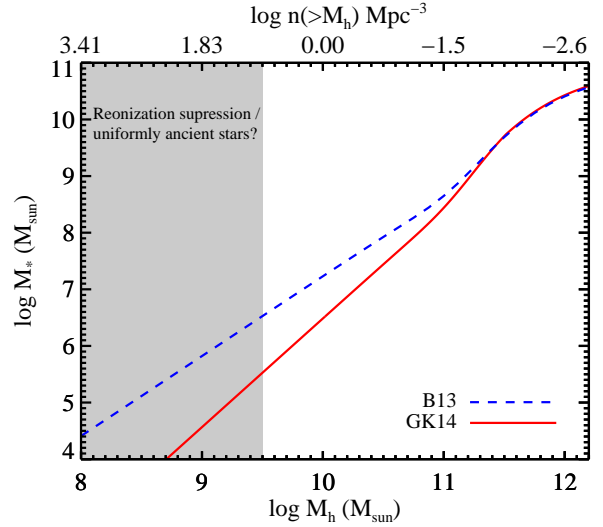

Figure 2. Stellar mass-halo mass relations. The upper x–axis has been converted to cumulative number density based on our fiducial cosmology. The B13 relation is a significant extrapolation beyond the mass range over which the original relation was constrained. The shaded region marks the approximate region where reionization is expected to quench star formation in low mass halos.

3. MODEL INGREDIENTS

In this section we present a model for the expected SN and nova rates from dwarf galaxies and intrahalo stars.

We start with the $z = 0$ dark matter halo mass function from Tinker et al. (2008). The halo virial mass is defined according to Bryan & Norman (1998). We adopt a Hubble constant of $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_m = 0.27 = 1 - \Omega_\Lambda$, and $\sigma_8 = 0.8$, consistent with the 7-yr WMAP results (Komatsu et al. 2011). These parameters are somewhat different from the recent Planck measurements (Planck Collaboration et al. 2015), but the differences have no material impact on our results.

Galaxies are placed within dark matter halos according to a stellar mass-halo mass ($M_* - M_h$) relation. Our fiducial relation is adopted from Garrison-Kimmel et al. (2014, GK14), which reproduces both the empirical galaxy stellar mass function at $z = 0$ and the Local Group dwarf luminosity function. The form of the $M_* - M_h$ relation at low masses is uncertain and has a large effect on our model predictions. In order to explore this sensitivity we will also consider the relation from Behroozi et al. (2013, B13), which we extrapolate well beyond the mass range probed by B13 (roughly $M_* = 10^8 - 10^{11} M_\odot$). The two relations are compared in Figure 2. We also indicate with a shaded band the approximate region where reionization is expected to quench star formation in low mass halos (e.g., Bullock et al. 2000). We adopt a relation with no scatter whereas in reality there may in fact be significant scatter at low masses (Wang et al. 2015, Garrison-Kimmel et al., in preparation). As long as the scatter is symmetric about the mean relation this will not affect our predicted rates.

The next step is to specify star formation histories (SFHs) for the dwarfs, as the SFHs will influence the SN rates. We adopt the following simple model: dwarf galaxies with $M_* > 10^5 M_\odot$ are assumed to have a constant SFR throughout their lifetimes, while less massive dwarfs are assumed to form all of their stars instantly at high redshift ($z > 2$). We consider in this work only dwarfs in the field, i.e., dwarfs that
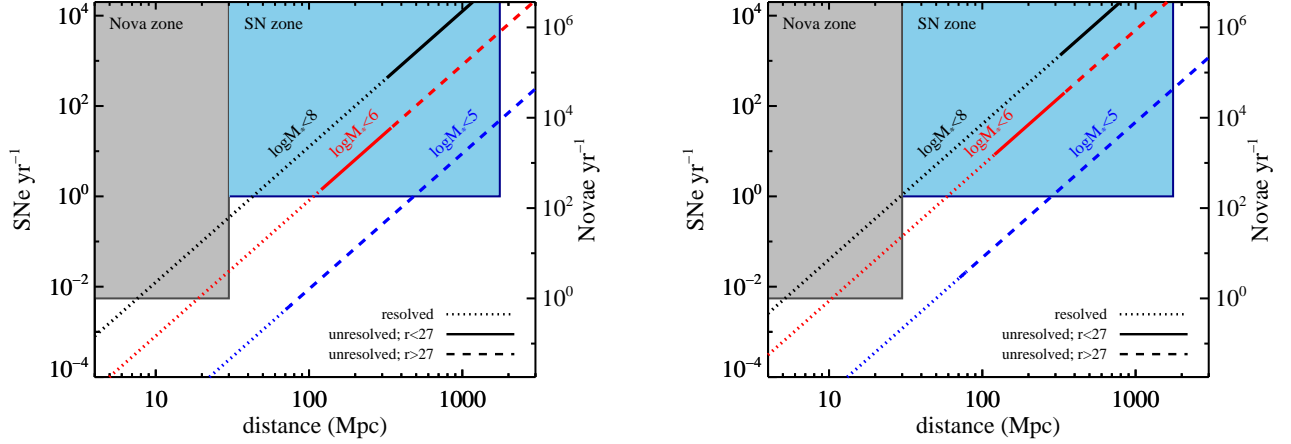
Figure 3. Predicted SN and nova rates as a function of distance adopting the GK14 (left) and B13 (right) stellar mass–halo mass relations. Lines show rates for dwarf galaxies with stellar masses less than $10^8 M_\odot$, $10^6 M_\odot$, and $10^5 M_\odot$. The shaded regions indicate where SNe and novae are detectable with a single LSST visit ($r < 24.3$) and where the rates are > 1 yr^{-1}. Each line is broken into three regions: where a typical galaxy would be spatially resolved (dotted), unresolved and brighter than $r = 27$ (solid) and both unresolved and fainter than $r = 27$ (dashed). This depth was chosen to be comparable to the final 10 yr LSST coadded depth of $r \approx 27.5$. Note that the SN/nova ratio is different for the lowest mass bin compared to the higher mass bins owing to the different assumed SFHs. The quoted nova rates on the y–axes are therefore only appropriate for the two most massive bins.

are not within the virial radius of a larger halo. This model is motivated by SFHs derived from resolved color magnitude diagrams of Local Group dwarfs (e.g., Weisz et al. 2014) and also consistent with expectations for dwarfs above and below this stellar mass threshold in cosmological simulations (e.g., Oñorbe et al. 2015, Wheeler et al. in preparation). Later, when converting masses into r–band magnitudes, we adopt $M/L_r = 1.8$ for the low mass galaxies with ancient metal-poor stellar populations and $M/L_r = 0.73$ for the higher mass dwarfs with constant SFHs (Conroy et al. 2009).

We will generically refer to SNe, noting that this includes both the core-collapse (CC) and type Ia varieties. For the CC SN rate we assume 1 per $100 M_\odot$ of newly formed stars, i.e., a galaxy with a star formation rate of $1 M_\odot$ yr^{-1} will have CC SN rate of 10^{-2} yr^{-1}. It is well-known that the rate of Ia SN depends on the age of the progenitor stellar population, with a delay time distribution (DTD) that falls approximately as t^{-1}. We adopt a DTD based on data presented in Maoz et al. (2012), with a rate at 10 Gyr of 3×10^{-14} yr^{-1} $M_\odot^{-1}$ and a time dependence of t^{-1}. With this DTD, a galaxy with a constant SFH will at the present epoch have a Ia rate of $\approx 10^{-13}$ yr^{-1} $M_\odot^{-1}$ (assuming the DTD is zero at $t < 10^8$ yr). The above assumptions imply that the CC rate is $10\times$ higher than the Ia rate for a galaxy with a constant SFH.

Distances to the SNe are required to use them to detect low redshift dwarf galaxies. For type Ia SNe, deriving distances from the light curve is straightforward. There has been some effort to use a subset of CC SNe (the "plateau" type) as standard candles (e.g., Schmidt et al. 1994; Hamuy & Pinto 2002). Hamuy & Pinto (2002) show a reasonably strong correlation between type IIP SNe apparent magnitude and redshift, which should be sufficient to at least discriminate between high and low redshift SNe. Spectroscopic follow-up of transients, which will no doubt occur for a subset of the events, will also be valuable for confirming the redshift of these apparently hostless SNe and therefore also the redshift of the underlying faint dwarf galaxy.

Nova rates have historically been difficult to empirically estimate owing to a variety of selection and incomplete-

ness effects. Nonetheless, observations of galaxies in the nearby universe are broadly consistent with a universal nova rate of 2×10^{-10} yr^{-1} $M_\odot^{-1}$, independent of Hubble type, galaxy color, etc. (Ciardullo et al. 1990; Ferrarese et al. 2003; Williams & Shafter 2004). There is however some evidence that the nova rate may increase toward lower mass galaxies (Neill & Shara 2005), which, if confirmed, would have important implications for the present study. Novae peak absolute magnitudes fall in the range from $-7 \lesssim M_V \lesssim -9$; in this work we adopt a typical peak magnitude of $M_r = -8$. The decay time of the nova light curve is inversely related to its peak brightness and the relation is sufficiently tight, and theoretically well-understood, so that one may be able to infer distances to novae from their light curves (e.g., Shara 1981; Downes & Duerbeck 2000).

Purcell et al. (2007) presented a simple model for the buildup of intrahalo light (IHL), where intrahalo stars are defined as residing within a parent dark matter halo but not bound to any particular galaxy. The model assigns stars to dark matter halos in a cosmological N–body simulation via an empirically-constrained $M_* - M_h$ relation, and when a dark matter subhalo is disrupted in the simulation the stars from that subhalo are assigned to the IHL. At the cluster scale, this model produces IHL fractions of order unity while at the Milky Way halo scale the IHL contributions are at the percent level; both of these predictions are in agreement with observations (e.g., Gonzalez et al. 2005; Irwin et al. 2005). We have fit their results with a polynomial function:

$$f_{\mathrm{IHL}}(M_h) \equiv \frac{M_{*,\mathrm{IHL}}}{M_{*,\mathrm{gal}}} = \sum_{i=0}^{3} a_i (\log M_h)^i, \qquad (1)$$

with $a_i = (9.5936, -5.3943, 0.5965, -0.01869)$, where $M_{*,\mathrm{IHL}}$ and $M_{*,\mathrm{gal}}$ are the stellar masses in the IHL and the central galaxy, respectively. The fit reproduces the model results to $5 - 10\%$. We assume that the intrahalo stars are uniformly old when computing nova and SN rates from this component. Integrating over the halo mass function, the above equation implies that the total stellar mass in the IHL is $\approx 10\%$ of the

stellar mass in galaxies.

4. RESULTS

The resulting model SN and nova rates for dwarf galaxies are shown in Figure 3 as a function of distance. We show results for two stellar mass-halo mass relations in order to highlight the sensitivity to the adopted relation. Clearly, observations of the SN and nova rate could place powerful constraints on the low mass end of the $M_* - M_h$ relation. Rates are shown for dwarfs with stellar masses less than $10^8 M_\odot$, $10^6 M_\odot$, and $10^5 M_\odot$. Along each line we mark where the most massive dwarfs would be resolved[4], unresolved and brighter than $r = 27$, and unresolved and fainter than $r = 27$. This depth was chosen to be comparable to the final, 10 yr coadded LSST depth of $r \approx 27.5$ (Abell et al. 2009). In order to compute when a dwarf would be resolved we have assumed effective radii of 0.8, 0.3, and 0.2 kpc for dwarfs with stellar masses of $10^8 M_\odot$, $10^6 M_\odot$, and $10^5 M_\odot$, respectively (see Fig 1). Shaded regions denote "sweet spots" where the rates are > 1 yr^{-1} and the transients are observable. In the case of novae the maximum distance is set by being able to detect a $M_r = -8$ nova in single epoch LSST data (though of course multiple epochs will be required to confirm that it is a nova), which will have a minimum depth of $r \approx 24.3$ (Abell et al. 2009). In the case of SNe the maximum depth is set by being able to detect a $M_r = -18$ SN in single epoch LSST data. This is a conservative limit as both type Ia and CC SNe can have peak magnitudes brighter than this. Finally, note that the quoted rates are for the entire (4π sr) observable volume, whereas in practice any survey will cover only a fraction of the sky at the necessary cadence.

The principle result of this Letter is that SNe and novae residing in low mass dwarf galaxies should be detectable in large numbers with upcoming time domain surveys such as LSST. Dwarfs in the mass range of $M_* \sim 10^5 - 10^6 M_\odot$ should be spatially resolvable to $10 - 100$ Mpc distances, but their low surface brightness, $\mu > 26$ mag arcsec^{-2}, will make it challenging to directly detect them. However, novae within these low mass galaxies will be detected at rates of $1 - 10^2$ yr^{-1} within ~ 30 Mpc, and SNe will be detected out to Gpc scales at rates of $\sim 10^2 - 10^4$ yr^{-1} (note that a comoving radial distance of 1 Gpc corresponds to $z = 0.25$ in our adopted cosmology). Even very low mass dwarfs with $M_* < 10^5 M_\odot$ will produce type Ia SNe at a rate of $\sim 10^2$ yr^{-1}. Relatively massive dwarfs ($M_* \sim 10^8 M_\odot$), should be easily detectable as spatially resolved, relatively high surface brightness objects out to several hundred Mpc distances. For these objects, detection via transients will likely be less interesting.

Figure 4 shows the expected SN and nova rates from intrahalo stars. Results are shown for stars within dark matter halos less massive than $10^{15} M_\odot$ and $10^{12} M_\odot$. The implied nova rates within 30 Mpc are fairly high, reaching nearly ≈ 500 yr^{-1} if one considers all IHL stars. A key difference between the transients associated with IHL stars and dwarfs is their spatial distribution - IHL stars are confined to within $0.1 - 1$ Mpc (depending on the virial radius of the host halo), while the dwarfs are presumably distributed throughout space, tracing the underlying dark matter distribution with a con-
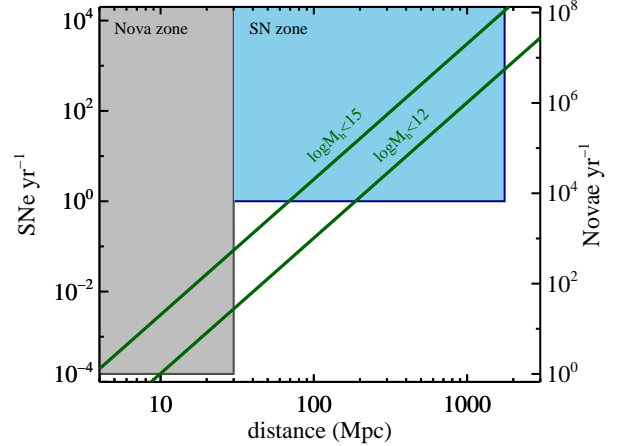

Figure 4. Same as Figure 3, except now for intrahalo stars residing in halos less massive than $10^{15} M_\odot$ and $10^{12} M_\odot$. The intrahalo stars are assumed to be uniformly ancient and so the SN/nova ratio is different here than in the y–axes in Figure 3.

stant anti-bias. The implied IHL rates are broadly consistent with, although somewhat lower than the predictions from Shara (2006). Shara assumed a global IHL fraction, $f_{\rm IHL}$, of $0.1 - 0.4$, whereas our model for the IHL, constrained by recent data, places this fraction at closer to 0.1.

5. DISCUSSION

Dwarfs at the mass scale $M_* \sim 10^5 - 10^6 M_\odot$ reside within some of the smallest dark matter halos that are expected to form stars - scales where the physics of reionization and dark matter may be probed with potentially powerful effect. Unfortunately, their use as cosmic laboratories to this point has been fundamentally limited by the fact that we detect them with reasonable completeness only within $\sim$Mpc volumes. As Figure 3 makes clear, the detection of (apparently) hostless SNe at $0.1 - 2$ Gpc distances should provide an important avenue for detecting these dwarfs and constraining the $M_* - M_h$ relation at low masses within volumes that are virtually immune to sample variance effects. In addition to counts, the ratio of type Ia to CC SNe will be a sensitive probe of the average SFH of the unresolved dwarfs. The correlation function of hostless SNe within a Gpc will provide constraints on the halo masses of the dwarfs and will allow for a statistical separation of transients arising from dwarfs and from intrahalo stars. One could also imagine analyzing the rates as a function of large scale environment to probe the low mass end of the galaxy population in e.g., void regions.

The majority of the dwarf galaxies detected via transients will be too distant for detailed study. We envision this detection technique as primarily a statistical probe of the low mass dwarf population. A dwarf with $M_* = 10^6 M_\odot$ and a constant SFH will have a CC SN rate of 10^{-6} yr^{-1}, so one must observe a volume containing 10^6 such dwarfs to detect one SN per year. This technique is only feasible because of the enormous numbers of predicted dwarf galaxies in the field.

A number of assumptions were made in computing the rate of luminous transients, the most important of which is the adopted $M_* - M_h$ relation. Other important assumptions include the SFH of the dwarfs and the assumed constant nova rate per unit stellar mass. We have assumed that galaxies

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[4] Here we use "resolved" and "unresolved" to refer to spatially resolving the galaxy, as opposed to resolving the galaxy into individual stars. We consider a galaxy "resolved" if the effective radius is $> 0''.5$.

with $M_* > 10^5 M_\odot$ have constant SFHs in the field. If instead some fraction are quenched or the star formation rates were higher in the past then the predicted SN rates will be lower. On the other hand, if the nova rate is in fact higher in dwarf galaxies, as suggested by Neill & Shara (2005), then the expected nova rate from dwarf galaxies could be much higher than assumed here. LSST and other transient surveys will directly constrain the nova rate in nearby dwarf galaxies with well-studied stellar populations, which will effectively eliminate the nova rate as a source of uncertainty. We have also assumed that the CC SN rate per unit star formation rate is constant and does not change with metallicity nor with the level of star formation rate. The latter in particular might affect the SN rate at levels where stochasticity and/or the effects of small cloud masses become important (e.g., Weidner & Kroupa 2004; da Silva et al. 2012). Here again LSST and other transient surveys will provide rates of CC SNe within known galaxies to inform a better model for the expected CC SN rate in low mass dwarfs. Finally, we have included CC SNe in the transient budget, but it is not clear if these will be as useful as novae and type Ia SNe due to the difficulty in assigning distances to CC SNe based only on the light curve. However, even in the most pessimistic case in which one discards the CC SN events, the predicted Ia rates for $M_* > 10^5 M_\odot$ are still substantial (approximately $10\times$ lower than shown in Figure 3). Moreover, recall that our model for the lowest mass galaxies ($M_* < 10^5 M_\odot$) assumes an ancient stellar population and hence the SNe associated with those galaxies are solely of the Ia variety.

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